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Emission line outflows in PKS1549-79: the effects of the early stages of radio source evolution?

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ABSTRACT
We present new spectroscopic observations of the southern radio galaxy PKS1549-79 ($z = 0.152$). Despite the flat spectrum character of the radio emission from this source, our optical spectra show no sign of the broad permitted lines and non-stellar continuum characteristic of quasar nuclei and broad line radio galaxies. However, the high ionization forbidden lines, including [OIII]$\lambda\lambda$5007,4959, are unusually broad for a narrow line radio galaxy (FWHM$\sim$1350 km s^{-1}), and are blueshifted by 600 km s^{-1} relative to the low ionization lines such as [OII]$\lambda\lambda$3726,3729. The [OII] lines are also considerably narrower (FWHM$\sim$650 km s^{-1}) than the [OIII] lines, and have a redshift consistent with that of the recently-detected HI 21cm absorption line system. Whereas the kinematics of the [OIII] emission lines are consistent with outflow in an inner narrow line region, the properties of the [OII] emission lines suggest that they are emitted by a more extended and quiescent gaseous component. We argue that, given the radio properties of the source, our line of sight is likely to be lying close to the direction of bulk outflow of the radio jets. In this case it is probable that the quasar nucleus is entirely obscured at optical wavelengths by the material responsible for the HI absorption line system. The unusually broad [OIII] emission lines suggest that the radio source is intrinsically compact. Overall, our data are consistent the idea that PKS1549-79 is a radio source in an early stage of evolution.

Key words: galaxies:active – galaxies:individual – galaxies:emission lines – quasars:general

1 INTRODUCTION

The near-nuclear narrow line region (NLR: $r < 5$kpc) is one of the brightest and most readily studied components of powerful radio galaxies. Yet, despite its potential importance for investigating gas flows close to the central energy source, and the relationship between optical quasar and radio jet activity (e.g. Rawlings & Saunders 1991), we are still far from understanding its basic structure, ionization and kinematical properties.

One important issue concerns the dominant gas acceleration mechanism and the nature of the narrow line kinematics. In terms of line widths, most powerful radio galaxies have [OIII] emission line widths in the range $300 < FWHM < 600$ km s^{-1} (Heckman et al. 1984). This is similar to the range measured in radio-loud quasars (Brotherton 1996) and Seyfert galaxies (Whittle 1992), and is entirely consistent with gravitational motions in the bulges of the host galaxies (Whittle 1992). However, a small but significant subset of radio-loud AGN show broader [OIII] lines ($FWHM > 800$ km s^{-1}) which may indicate non-gravitational motions. Interestingly, these broader lines are invariably associated with compact radio sources, including compact steep spectrum (CSS) and gigahertz-peaked (GPS) sources (Gelderman and Whittle 1994). There is growing evidence that such compact radio sources are younger than their more extended counterparts (e.g. Fanti et al. 1995). Therefore, the differences between the linewidth distributions of compact and extended radio sources suggest that the properties of the NLR evolve as the radio sources expand through the haloes of the host galaxies.

Apart from the relatively crude line width measurements, more sophisticated analyses of the line profiles reveal evidence for radial motions in at least some classes of active galaxies. Most notably, measurements of the line asymmetry index AI20 provide evidence for an excess of blue asymmetries in the wings of the [OIII] lines in Seyfert galaxies (Heckman et al. 1984, Whittle 1992). However, the evidence for systematic radial flows in the population of radio-loud AGN is more controversial. While Brotherton et al. (1996)

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found an excess of blue asymmetries in a sample of high redshift radio-loud quasars, Heckman et al. (1984) found no such excess in a sample of low redshift radio galaxies.

It is important to establish the direction of any radial flows. For example, if it could be shown that the gas is predominantly outflowing, then this would provide clear evidence for non-gravitational motions associated with the AGN. Unfortunately, analyses of the profiles of single emission lines do not provide a clear-cut answer, because the interpretation of the line asymmetries depends on the (uncertain) distribution of dust in the NLR. Given the recognition that AGN-induced outflows may be an important feedback mechanism in formation of massive galaxies (e.g. Silk & Rees 1998, Fabian 1999), the issue of the existence, or otherwise, of radial outflows has a more general significance than the detailed phenomenology of active galaxies.

It is clear that there is considerable uncertainty surrounding the nature of NLR kinematics in powerful radio galaxies. In this paper we present spectroscopic observations of the unusual flat-spectrum radio source PKS1549-79 which provide strong evidence for outflow in the NLR, and have a bearing on our general understanding of the structure, kinematics and evolution of the NLR in radio galaxies.

2 PREVIOUS OBSERVATIONS OF PKS1549-79

The radio source PKS1549-79 was first identified with a galaxy by Prestage & Peacock (1983). Subsequent spectroscopic observations by Tadhunter et al. (1993) revealed a high ionization narrow line spectrum, with no sign — at least at the wavelengths covered by the observations ($\lambda < 5500$Å) — of broad permitted lines that would lead the object to be classified as a BLRG or quasar. The redshift measured from the [OIII] emission lines in the early observations was $z = 0.150$. However, even at the low spectroscopic resolution (>20Å FWHM) of the early observations it was clear that the forbidden lines are unusually broad in this object. A further unusual feature is that both the [OIII] lines and 5000Å continuum are polarized at the P∼3% level, indicating a significant, but not dominant, contribution from scattered or dichroically absorbed INLR light (di Serego Alghieri et al. 1997). The fact that a similar degree and orientation of the polarization are measured in the lines and continuum provides strong evidence against a non-thermal origin for the polarized continuum.

PKS1549-79 is also interesting because it is one of the few known radio galaxies which has an optical continuum that is dominated by the light of a young stellar population (Dickson 1997, Dickson et al. 2000), with the higher order Balmer lines clearly visible in absorption in the spectrum presented by di Serego Alighieri et al. (1997). Another possible sign of star formation in this source is the unusually strong far-IR emission detected by the IRAS satellite (Roy & Norris 1996).

Unusually for a narrow line radio galaxy (NLRG), PKS1549-79 is a compact flat spectrum source. It is difficult to be precise about the radio spectral index, because of the non-simultaneity of many of the radio observations and the possibility of radio source variability, but certainly at the higher radio frequencies the radio spectrum appears relatively flat ($\alpha \sim 0.0$: Morganti et al. 1993). Moreover, the relatively large scatter in the flux measurements at particular frequencies taken at different epochs indicates a degree of radio variability (e.g. Gaensler & Hunstead 2000), although some of this variability may be due to interstellar scintillation, given the relatively low Galactic latitude of the source.

In common with many flat spectrum radio sources, VLBI observations of PKS1549-79 reveal a one-sided jet structure emanating from an unresolved core source, with the unresolved core dominating the flux at the higher radio frequencies (Murphy et al. 1993, King 1994). The jet has a distorted structure — bending through an angle of 60° on the NE side of the nucleus — and a steep radio spectrum, whereas the unresolved radio core has a relatively flat spectrum. The total extent of the radio source in the VLBI map is ∼150mas (∼540pc*), and it has been estimated that the core-jet structure contributes 95% of the total flux at 2.3GHz (King 1994). There is no evidence for structure on larger scales from lower resolution maps. Overall, the relatively small extent, one-sided structure, flat spectrum and variability of the radio source are similar to those observed in flat-spectrum radio sources in general.

A final interesting feature of PKS1549-79 is that significant HI 21cm absorption has been detected against its radio core (Morganti et al. 2001). In an attempt to gain an accurate optical emission line redshift for comparison with the HI 21cm redshift, we took intermediate dispersion spectroscopic observations of PKS1549-79 in September 1998. These observations are described below, along with lower spectral resolution observations taken in 1995.

3 NEW SPECTROSCOPIC OBSERVATIONS OF PKS1549-79

The spectroscopic observations reported here were taken on the ESO 3.6m telescope with the EFOSC1 (1995) and EFOSC2 (1998) spectroscopic/imaging instruments. Use of the B300 grating with EFOSC1 in 1995, and the O150 grating with EFOSC2 in 1998, resulted in spectroscopic resolutions of 25Å and 12.8Å respectively. For the 1998 observations the use of a slit narrower (1.5 arcseconds) than the estimated seeing disk, and the alignment of the slit with the parallactic angle, removed any uncertainties that might result from the different spatial distributions of the various emission lines in the spectroscopic slit. The seeing was approximately 2 arcseconds (FWHM) for both runs.

The data from the 1995 run were reduced following the standard steps of bias subtraction, flat fielding, wavelength calibration, atmospheric extinction correction and flux calibration. The reduction for the 1998 data — which have a generally lower S/N but a better spectroscopic resolution — followed the same steps, except that no atmospheric extinction correction and flux calibration were performed. Comparison between the results for various flux calibration standards observed during the 1995 run reveals that the relative flux calibration is accurate to within ±5% for the 1995 run, while measurements of various night sky emission lines show that the wavelength calibration is accurate to better ±1Å

* $H_0 = 50$ km s^{-1}, $q_0 = 0.0$ assumed throughout, resulting in a scale of 3.59 kpc arcsec^{-1} for $z = 0.152$.

Figure 1. Optical spectrum of PKS1549-79 extracted from the 1995 low resolution data.

Line	**Rest Wavelength (Å)**	**Relative Flux**	**Measured Wavelength (Å)**	**Redshift**	**Line Width FWHM(km s^{-1})**
[NeV]	3425.6	43	3942.0±1.4	0.1506±0.0004	1100±300
[OII](high density)	3728.8	135	4297.9±1.0	0.1526±0.0002	650±150
[OII](low density)	3728.8	135	4296.7±1.0	0.1523±0.0002	650±150
[NeIII]	3868.8	91	4449.1±1.6	0.1500±0.0004	1650±220
HeII	4685.7	40	—	—	—
Hβ	4861.3	100	5599.1±3.1	0.1518±0.0004	1700±500
[OIII]	4958.9	386	5703.7±1.0	0.1502±0.0002	1420±60
[OIII]	5006.9	1156	5758.3±1.0	0.1501±0.0002	1315±25
[OI]	6300.3	—	7259.7±1.9	0.1523±0.0003	480±300

Table 1. Emission line wavelengths, relative fluxes, redshifts and rest-frame widths (FWHM) for PKS1549-79. Note that the emission line wavelengths, redshifts and line widths have been measured from the 1998 intermediate-resolution data, whereas the line fluxes (presented relative to $H\beta = 100$) have been measured from the lower resolution 1995 data. The relative line fluxes have an accuracy of approximately ±10%, and the line widths have been quadratically corrected for the instrumental width (12.8Å, FWHM). The [OII]$\lambda\lambda$3726,3728 blend has been fitted using two Gaussians which have been constrained to have the same width, and with the separation between the lines set by the atomic physics. In making these fits the [OII](3726/3729) ratio has also been constrained by making two different assumptions about the electron density in the emitting region (high density limit and low density limit). Note that the results for Hβ are likely be less accurate than for the other lines, because of the proximity of the bright [OI]λ5577 night sky line.

over the entire useful wavelength range for the 1998 observations, and to within ±5Å for the 1995 observations (but this assumes a filled slit).

The observations were reduced using the Starlink FIGARO package and analysed using the Starlink DIPSO spectroscopic analysis package.

4 RESULTS

First we consider the narrow line spectrum based on the 1995 data, which have a relatively high S/N and good flux calibration. Table 1 shows the relative emission line strengths derived from these data, following subtraction of a continuum template as outlined in Dickson (1997), while Figure 1 shows a plot of the spectrum. It is clear from these results that the emission line ratios measured in PKS1549-79 fall within the range measured for radio galaxies in general (e.g. Cohen & Osterbrock 1981), albeit at the higher ionization end of the range.

Despite the apparently "normal" emission line ratios, clear differences exist between the kinematical properties of the various emission lines. These differences were first noticed in our lower resolution data taken in 1990 and 1995,

but were confirmed with the higher spectral resolution data taken in 1998. Table 1 shows the wavelengths, redshifts and rest-frame line widths measured from the 1998 data by fitting single Gaussian profiles to the stronger emission lines.

A striking feature of the redshift measurements is that the higher ionization lines — [OIII]$\lambda\lambda$5007,4959, [NeIII]λ3869, [NeV]λ3426 — have a significantly lower redshift ($\overline{z} = 0.1501 \pm 0.0001$) than the low ionization lines – [OII]λ3727 and [OI]λ6300 ($\overline{z} = 0.1522 \pm 0.0002$). The redshift difference ($\Delta z = 0.0021 \pm 0.0002$) corresponds to a rest-frame radial velocity difference of $\Delta v = 600 \pm 60$ km s^{-1}. We note that the redshift of the low ionization system is consistent with that of the HI 21cm absorption (Morganti et al. 2000). A further important feature is that the high ionization lines are significantly broader ($FWHM$ ~1350 km s^{-1}) than the low ionization lines ($FWHM$ ~600 km s^{-1}).

In order to gain further clues to the structure of the NLR in this object, we have investigated the spatial distributions of the emission lines relative to the continuum, by using Gaussian fits to the spatial slices extracted from the 1995 long-slit data. The results show that the positions of the fitted centres of [OII], [OIII] and continuum distributions along the slit (PA270) are all consistent within the errors ($\pm$0.1 arcseconds). However, following quadratic correction for the seeing disk using measurements of stars along the slit, we find that the [OII] emission is more spatially extended ($FWHM = 2.74 \pm 0.25$ arcseconds or 9.8 ± 0.9 kpc) than the barely-resolved [OIII] emission ($FWHM = 0.84 \pm 0.2$ arcseconds or 3.0 ± 0.72 kpc).

How unusual are these emission line properties? Redshift differences between high and low ionization narrow lines appear rare, having been noted before in only a handful of active galaxies (e.g. Koski 1978). Note, however, that the true rate of occurrence of such redshift differences is difficult to gauge, because accurate comparisons between the redshifts of the various lines are not always reported when emission line spectra are presented in the literature. What is clear is that the line widths measured in PKS1549-79 are extreme. Very few active galaxies at low redshifts — fewer than 5% of those with the accurate line width measurements — are known to have [OIII] lines broader than 1000 km s^{-1}, and those that do are either Seyfert galaxies with powerful linear radio sources (Whittle 1992) or, amongst radio-loud AGN, intrinsically compact radio sources (Gelderman & Whittle 1994).

We note in particular the remarkable similarities between PKS1549-79 and the GPS sources PKS1345+12 (4C12.30) and 3C48. Both of these latter sources also show unusually broad [OIII] emission lines ($FWHM$ = 1350 km s^{-1} in PKS1345+12 and $FWHM$ = 1650 km s^{-1} in 3C48: Gelderman and Whittle 1994), with the high ionization lines significantly broader and blueshifted relative to the low ionization lines in PKS1345+12 (Grandi 1977); both sources have unusually luminous far-IR emission; and both sources have relatively compact radio sources with one-sided jets. The major difference between these two sources and PKS1549-79 is that their radio cores are weaker and they show less evidence for variability at both low and high frequencies.

Overall, the extreme NLR kinematics observed in PKS1549-79 have more in common with the class of intrinsically compact radio sources ($D <$ 15kpc) than with the general population of extended radio sources.

5 DISCUSSION

5.1 The structure of the NLR in PKS1549-79

The kinematic differences between the low and high ionization lines provide clear evidence for at least two distinct components to the NLR in PKS1549-79: a kinematically disturbed component that is compact and emits most of the high ionization line flux; and a more quiescent component that has a larger spatial extent and is associated with the HI 21cm absorption and low ionization line emission.

The most attractive explanation for the kinematic differences between these components is that the high ionization lines are formed in a region close to the central AGN, perhaps an inner narrow line region (INLR) which is undergoing systematic outflow. On the other hand, the low ionization lines are formed in a region at greater nuclear distances which is not disturbed kinematically by the jets or nuclear activity, and which has a radial velocity close to systemic.

At present we cannot entirely rule out the alternative explanation: that the [OIII] lines have a redshift close to systemic and the HI and [OII] are associated with an infalling gas cloud or companion galaxy which is redshifted relative to systemic. However, this explanation is less attractive because the width the [OII] lines ($FWHM$ ~650 km s^{-1}) would imply a large gravitational mass for the infalling companion, yet existing ground-based imaging observations fail to reveal any evidence for a massive companion galaxy along the line of sight; the nearest object visible in ground-based images is situated 6.7 arcseconds (24kpc) to the West (Prestage & Peacock 1983) of the nucleus of PKS1549-79, but our spectroscopic observations show that this is a Galactic star. It is also unlikely that the spatial centres of the [OII] and [OIII] emission line distributions along PA270 would match up so accurately if the lines were emitted by separate galactic systems.

In an attempt to gain more information about the ionization states of the two kinematic components using the [OII](3727)/[OIII](5007) diagnostic ratio, we have made two component Gaussian fits to the [OIII]$\lambda\lambda$5007,4959 and [OII]λ3727 lines, in order to determine the maximum contributions of, respectively, the broad component to [OII] and the narrow component to [OIII]. We find that, for acceptable fits to the line profiles, the narrow component contributes <25% of the total flux of [OIII], while the broad component contributes <35% of the [OII] flux. Then, using the line ratio information from Table 2, we find that $[OII](3727)/[OIII]5007) < 0.05$ for the broad component, and $[OII](3727/[OIII]5007) > 0.6$ for the narrow component.

The upper limit on [OII](3727)/[OIII](5007) for the broad component is unusually small for a radio galaxy. Indeed, in a recent spectroscopic survey of 20 intermediate redshift radio galaxies by Dickson et al. (2001), none of the objects showed such a small value for this line ratio. The small [OII](3727)/[OIII](5007) might imply an unusually high ionization state, a high density and/or a large reddening for the

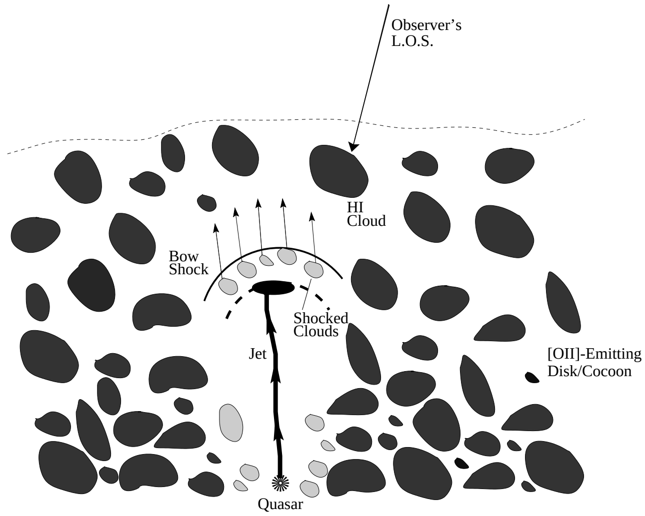

Figure 2. A schematic diagram showing a plausible geometric arrangement for the various emitting components in PKS1549-79. The [OIII]-emitting clouds are shaded light grey; most of the [OII] is emitted by material in the extended disk/cocoon (shaded black).

region emitting the broad lines. However, the relatively large [NeV](3426)/[NeIII](3869) and HeII(4686)/Hβ ratios measured from the low resolution spectrum (Table 1) suggest that the broad component has a genuinely high ionization state. Overall, the emission line spectrum of the broad component appears more consistent with AGN photoionization models that include matter-bounded components (Binette et al. 1996), than with shock models (e.g. Dopita & Sutherland 1996).

Finally we note that the [OII](3727)/[OIII](5007) ratio deduced for the narrow component suggests a moderately low ionization state, but without further information we cannot distinguish between AGN photoionization, shock ionization or stellar photoionization for this component.

5.2 PKS1549-79 and radio source populations

In terms of the orientation-dependent unified schemes for powerful radio galaxies (e.g. Barthel 1989), we would expect PKS1549-79 to show the optical characteristics of classes of radio-loud active galaxies which share its radio properties, such as BL Lac objects, blazars or quasars. However, PKS1549-79 does not fit in easily with any of these optical classifications. Not only does it lack the non-thermal optical continuum chracteristic of blazars and BL Lac objects, but its narrow emission lines are much stronger than expected for a BL Lac object; the absence of broad permitted lines lines also rules out a quasar classification.

It is important to consider how the optical and radio propertes of PK1549-79 can be reconciled. A possible clue is provided by the HI 21cm absorption feature, which has a similar redshift to the narrow, low ionization emission line component. As discussed by Morganti et al. (2001), the HI absorption characteristics are consistent with an absorbing column density in the range $3.6\times10^{20} < N(HI) < 2.9\times10^{22}$ cm^{-2}, depending on the spin temperature ($100 < T_{spin} < 8000$K). For normal gas/dust ratio and dust extinction properties, this translates into a visual extinction in the range $0.23 < A_v < 18$ magnitudes. At the lower end of this range the central AGN would be lightly extinguished, whereas at the upper end of extinction range, it would be wholly extinguished at optical wavelengths (see Simpson et al. 1999). Therefore the most plausible explanation for the optical properties of this source is that the blazar, quasar or BL Lac nucleus is extinguished by dust associated with the ISM that also produces the HI absorption and narrow emission line component. In this case the broad, high ionization emission line component may be photoionized by the hidden nucleus, but be distributed such that it does not suffer the same degree of extinction.

At first sight this explanation appears inconsistent with the simplest versions of the unified schemes, which hold that we should have a relatively unobscured view of the optical nucleus when the jet is pointing close to the line of sight. Recently, however, the detection of a population of relatively red flat-spectrum quasars has led to the suggestion that dust extinction may nonetheless be important in flat spectrum quasars (Webster et al. 1995 but see Baker 1997). Our results for PKS1549-79 support this suggestion, although other reddening mechanisms, such as a contributions from red, non-thermal synchrotron sources (Serjeant & Rawlings 1996), and contamination by the light of the stellar populations of the host galaxies (Benn et al. 1998), are also likely to be important at some level.

Whether or not we accept the variable dust extinction model for the population of flat spectrum radio sources, it is clear that amongst such sources the quasar nucleus in PKS1549-79 is unusually highly extinguished. This high extinction may be linked to the unusual emission line kinematics discussed in section 4 as follows. We have argued that the extreme emission line widths measured in PKS1549-79 are consistent with it belonging to the class of intrinsically compact radio sources. Such sources are thought to be either objects in which the radio jets are trapped in the central regions of the host galaxies by an unsually dense ISM (the so-called "frustration" model: van Breugel 1984), or objects observed in a relatively early stage of their evolution, before the radio jets have expanded out of the central regions of the galaxies (the "youth" model: see Fanti et al. 1995 for a discussion). In the frustration model we would naturally expect a substantial extinction to the central AGN, even when the jet is pointing close to our line of sight. Less obviously, we might also expect substantial extinction along the radio jet axis in the youth model. This is because, when the radio jets are first formed, the nucleus is likely to be surrounded by a cocoon or thick disk of material left over from the events which triggered the nuclear activity. In at least some cases the obscuring material may cover large fraction of the sky as seen by the central source. As the radio source evolves, any obscuring material along the radio axis is likely to be swept aside and dissipated by jet-cloud interactions (e.g. Bicknell et al. 1997) or quasar-induced winds (e.g. Balsara & Krolik 1993) until, eventually, cavities are hollowed out on either side of the nucleus. Such cavities have been detected, for example, in the powerful extended radio source Cygnus A (Tadhunter et al. 1999). Before this stage is reached, however, a substantial amount of obscuring material may be present along the radio axis, but at larger radial distances from the nucleus than the radio source.

A possible model for PKS1549-79, which shows the geometric arrangement of the various radio and optical components, is shown schematically in Figure 2.

The general idea that the quasar nucleus is obscured in PKS1549-79 receives indirect support from the detection of a broad Paschen α emission line in infrared observations of the similar source PKS1345+12 (Veilleux et al. 1997). The broad Paschen α line in PKS1345+12 is thought to be emitted by a quasar nucleus which is extinguished at optical wavelengths ($A_v > 6.5$ magnitudes). Clearly, infrared observations aimed at detecting a similar broad Paschen α feature in PKS1549-79 would provide a decisive test of the model we have proposed for this source.

6 CONCLUSIONS AND FUTURE WORK

Most plausibly, PKS1549-79 is an intrinsically compact radio source that has its radio jet axis pointing close to our line of sight, and its quasar nucleus obscured from our direct view by a large amount of obscuring material along the radio axis. While the gas responsible for the broad, high ionization emission line component may be photoionized by the hidden quasar nucleus, it is likely that this component is accelerated by AGN-induced outflows. In this case, we have caught this source in an early stage of its evolution, as the radio jets tunnel their way through the cocoon of debris left over from the events which triggered the activity.

A major implication of this work is that the simplest versions of the unified schemes, in which lines of sight close to the radio jet axis have a relatively unobscured view of the quasar nucleus, may not always hold for young, compact radio sources in which the jets and/or quasar winds have not yet swept aside the warm ISM in the ionization cones on either side of the AGN. This ties in with the mounting evidence that the quasar nuclei in the population of compact radio sources may suffer more extinction than in extended radio sources (e.g. Baker & Hunstead 1995, Baker 1998).

Clearly, detailed spectroscopic observations of larger samples of compact radio sources have the potential to provide key information about both the early stages of radio source evolution and the effects of the AGN activity on the ISM of the host galaxies.

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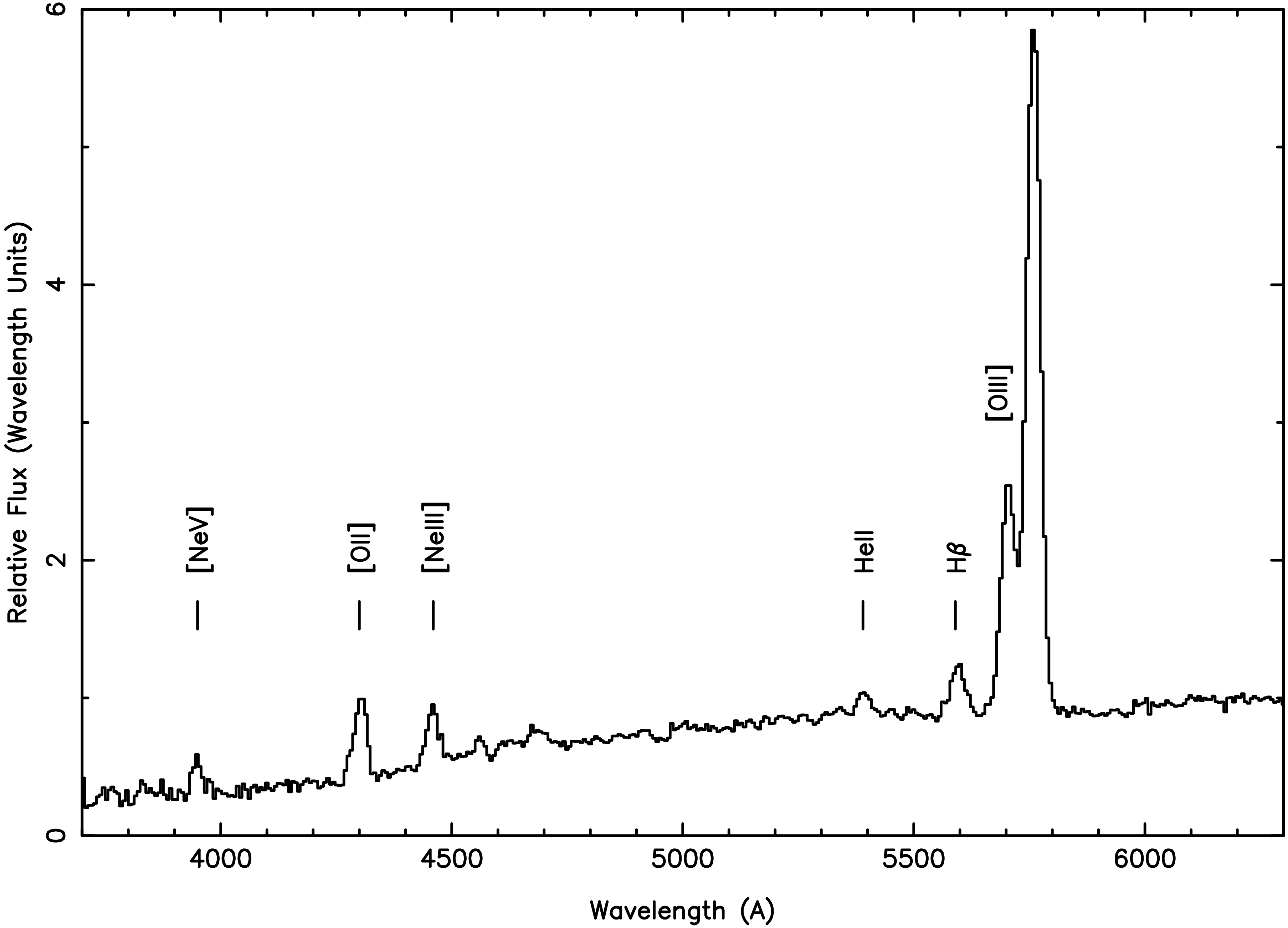
PKS1549−79



[NeV]
[OII]
[NeIII]
HeII
Hβ
[OIII]
Relative Flux (Wavelength Units)
0
2
4
6
4000
4500
5000
5500
6000
Wavelength (A)